Late Jurassic to Early Cretaceous sedimentary-tectonic development in the Chengde Basin, Yanshan fold-thrust belt, North China Craton

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Abstract

The Chengde Basin is located in the central part of the Yanshan fold-thrust belt in the northern North China Craton. The sediments in the Upper Jurassic to Lower Cretaceous Tuchengzi Formation in the Chengde Basin provide a detrital record of basin dynamics and uplift of the basin margins during that time. We analyzed the sedimentary facies, paleocurrents, and provenance of the Tuchengzi Formation in the Chengde Basin for the period of the Late Jurassic and Early Cretaceous shortening in the Yanshan fold-thrust belt. Four sedimentary facies associations have been identified in the Tuchengzi Formation, corresponding to proximal fan, mid-fan, distal alluvial fan, and fluvial facies. The transport and distribution of the Upper Jurassic to Lower Cretaceous sediments in the Chengde Basin was controlled by the faults bounding the basin. Paleocurrent indicators and provenance data of conglomerate clasts reveal that the sediments of the Tuchengzi Formation in the northern part of the Chengde Basin were delivered from source regions to the north of the basin. The early sediments of the Tuchengzi Formation in the southern part of the basin comprise a suite of fluvial deposits, similar to the fluvial sediments in the northern part of the basin, and their paleocurrent data and the compositions of conglomerate clasts also suggest a northern source. However, the subsequent sedimentation in the Tuchengzi Formation in the southern part of the basin changed markedly to proximal fan facies, with sediments being derived from the south of the basin, according to the paleocurrent data and conglomerate clast lithology. The Sandaohe sheet, which is located in the southeast limb of the Chengde syncline, is not a klippe formed as a result of long-distance northward thrusting, but an autochthonous pop-up tectonic wedge generated by N–S shortening during the Early Cretaceous sedimentation of the Tuchengzi Formation. The sedimentation ended before the onset of the Early Cretaceous volcanic eruption recorded by the Zhangjiakou Formation, which unconformably overlies the Tuchengzi Formation.

1. Introduction

After the North China Craton (NCC) collided with the Mongolian arc terranes during the late Paleozoic, the northern edge of the NCC evolved from a plate margin to an intraplate environment (Davis et al., 2001). The Yanshan fold-thrust belt (YFTB) is located near the northern margin of the North China Craton (Fig. 1), and experienced at least two major episodes of compressional deformation during the Mesozoic. The first contraction occurred during the Late Triassic and Early Jurassic, and the second compression, also known as the “Yanshanian movement” or “Yanshanian event”, occurred during the Late Jurassic and Early Cretaceous (Wong, 1927; Cope et al., 2007).

The Chengde Basin is located in the central segment of the YFTB, with its northern margin bounded by the Fengning-Longhua Fault and its southern margin by the Chengde County Fault (Figs. 1 and 2). A 20-km-wide asymmetric syncline, called the Chengde syncline, lies between the Shuangmiao Fault in the central part of the basin and the Jiyuqing Fault at the southern margin of the basin (Fig. 2). Although strongly deformed in the Jurassic Yanshanian movement, the Chengde Basin offers a crucial location for studying the context of the tectonic-sedimentary response, because of the relatively complete preservation and good outcrops of Mesozoic sedimentary rocks within the basin.

Basin-fill sediments are records of contemporaneous tectonic activities, and can provide constraints not only on paleogeographic conditions, but also on the timing and magnitude of shortening.
and associated thickening (e.g., Liu et al., 2004, 2012; He et al., 2007; Cope et al., 2007). Thus, in combination with structural relationships and geochronology, sediments can be used to address the depositional environments, provenance characteristics, and development and deformation of the sedimentary basins in the Yanshan belt during the Late Jurassic–Early Cretaceous shortening. Some previous structural and geochronologic studies have interpreted the Chengde syncline as representing a folded allochthon that resulted from long-distance north-vergent thrusting with a displacement of at least 40 km (Davis et al., 1998, 2001). In contrast, other studies have provided geometric, kinematic, stratigraphic, provenance, and geochronologic evidence that the faults bounding the northern and southern limbs of the Chengde syncline (i.e., the Shuangmiao and Jiyuqing faults) are two separate thrust faults with opposing north and south vergence rather than a single folded north-directed thrust, and that the sedimentary rocks within the syncline are not allochthonous (e.g., Zhao et al., 2004; Cope et al., 2007; He et al., 2007; Zhang et al., 2012). Although there is now a consensus that the Chengde syncline is not a nappe, the formation of the Tuchengzi sheet, which is located in the southeast limb of the Chengde syncline, is not well constrained. The Tuchengzi sheet is dominated by Meso–Neoproterozoic carbonate rocks and is surrounded by Upper Jurassic Tiaojishan volcanic rocks. Knowledge of its method of formation is important for understanding the scale of the compressional deformation in the Yanshan fold-thrust belt during the Late Jurassic and Early Cretaceous; that is, whether the Yanshan fold-thrust belt experienced long-distance northward thrusting during this interval, as suggested by Davis et al. (2001), or instead relatively limited N–S shortening.

In this study, we investigate the Upper Jurassic–Lower Cretaceous Tuchengzi Formation across the Chengde Basin from north to south, employing detailed sedimentary facies relationships and provenance analysis. Four sedimentary facies associations are identified, corresponding to proximal fan, mid-fan, distal alluvial fan, and fluvial environments. We demonstrate that the Tuchengzi sediments in the northern part of the Chengde basin and the early Tuchengzi sediments in the southern part of the basin were transported from source areas to the north of the basin, whereas the subsequent Tuchengzi sediments in the southern part of the basin were derived from the south. In particular, we highlight that rapid uplift and erosion of the Sandohe sheet at the southern margin of the Chengde syncline provided substantial amounts of material for the Tuchengzi Formation in the southeastern Chengde basin.

2. Geological background

2.1. Geological setting

The northern margin of the NCC, which is located southeast of the Central Asian Orogenic Belt, is divided into two E–W-trending tectonic units by the Pingquan–Gubeikou Fault (also referred to as the Shangyi–Gubeikou–Pingquan Fault; HBGMR, 1989). The two units are named the Inner Mongolia Paleo-Uplift (IMPU) in the north and the Yanshan fold-thrust belt (YFTB) in the south (Fig. 1). The IMPU is characterized by extensive Archean–Proterozoic high-grade basement rocks that are unconformably overlain by Jurassic–Cretaceous volcanic and sedimentary rocks. The entire tectonic province was exhumed during the late Carboniferous to Early Jurassic (Zhao, 1990; Zhang et al., 2007).

The YFTB consists mainly of a Paleoproterozoic basement, Mesoproterozoic sediments, Cambrian to Ordovician marine clastic and carbonate platform sediments, middle Carboniferous to Triassic fluvial and deltaic sediments, and Jurassic to Cretaceous (and
younger) volcanic and sedimentary rocks. The maximum thickness of the Mesoproterozoic and early Paleozoic strata in the YFTB is ca. 11.5 km (HBGMR, 1989), but these units are almost entirely absent from the IMPU, except for some Mesoproterozoic sedimentary rocks that form a narrow belt along the Fengning-Longhua Fault (Fig. 1).

2.2. Characteristics of thrust faults in the Chengde Basin

The major thrust faults in the Chengde area are generally east–west trending. The most important fault structures in the Chengde Basin (Fig. 1) are the Fengning-Longhua Fault (FL F.) to the north and the Chengde County Fault (CC F.) to the south, but several second-order faults have also been mapped (Davis et al., 2001; HBGMR, 1989; Fig. 2).

The Paleoproterozoic Fengning-Longhua Fault (Fig. 2) is the northern boundary of the Yanshan belt (Fig. 1; HBGMR, 1989). The footwall consists of Archean rocks, which are unconformably overlain by Upper Jurassic to Lower Cretaceous conglomerates and Lower Cretaceous volcanic rocks (HBGMR, 1989). This fault experienced intense tectonic activity during the late Paleozoic and Mesozoic. It now forms the northern boundary of the Jurassic Chengde Basin, and exerted a strong control on basin development during the Late Jurassic and Early Cretaceous (HBGMR, 1989; Liu et al., 2004; He et al., 2007).

The Chengde County Fault (Figs. 2 and 3) experienced tectonic activity during the Late Jurassic and Early Cretaceous and this fault marks the southern boundary of the Chengde Basin (Zhang et al., 2004a). From bottom to top, the hanging wall of the Chengde County Fault consists of: (1) Mesoproterozoic carbonate rocks of the Jixian Group, which are buff-colored, thinly bedded to stromatolitic dolomites containing variable amounts of chert; (2) thinly bedded, white, laminated limestones interbedded with black shales of the Neoproterozoic Qingbaikou Group, within which diabase sills (up to ca. 50 m thick) are present; (3) Paleozoic (Cambrian–Ordovician) carbonates consisting of blue to blue-gray, mottled or banded limestones and sparse, dark-brown dolomites; and (4) volcanic rocks of the Upper Jurassic Tiaojishan Formation.

The Shuangmiao Fault (SM F.) in the central part of the Chengde Basin and the Jiyuqing Fault (JYQ F.) at the southern margin of the basin mark respectively the northern and southern boundaries of the Chengde syncline (Fig. 2), an asymmetric syncline that is 20 km wide from north to south. The Shuangmiao Fault (Fig. 3) is a south-dipping thrust. A narrow belt of the Proterozoic Changcheng Group crops out on the hanging wall of the fault. The footwall contains conglomerates of the Upper Jurassic–Lower Cretaceous Tuchengzi Formation, which is folded at some places close to the fault plane. Slickensides, together with the folded structure, indicate northward movement of the Shuangmiao Fault. The Jiyuqing Fault (JYQ F., Fig. 3) is a steeply north-dipping thrust, with the Proterozoic Changcheng Group on the hanging wall and the Upper Jurassic volcanic rocks of the Tiaojishan Formation on the footwall.
The steeply south-dipping Hualiangou-Hedong Fault (HH F., Fig. 3) marks the northern boundary of the lenticular Sandaohe sheet (Zhao et al., 2004), the southern boundary of which is the Jiyuqing Fault. The footwall of the Hualiangou-Hedong Fault consists of Upper Jurassic volcanic rocks of the Tiaojishan Formation, and the hanging wall is made up of Proterozoic chert-bearing carbonate rocks of the Jixian Group. Our field observations show that a limited area of the Tiaojishan volcanic rocks lie unconformably on Proterozoic carbonate rocks within the Sandaohe sheet (Fig. 3).

2.3. Age of the Tuchengzi Formation in sedimentary basins of the central YFTB

The Tuchengzi Formation is widely distributed and trends E–W in the northern part of North China. The Tuchengzi Formation rests unconformably on pre-Mesozoic units at Chicheng in northern Hebei Province, but elsewhere it commonly overlies Upper Jurassic rocks known as the Tiaojishan (Lanqi) Formation, which is composed predominantly of andesitic, trachyandesitic, and pyroclastic
rocks. The contact relationships between the Tuchengzi Formation and the underlying Tiaojishan Formation are generally described as disconformable or conformable (HBGMR, 1989; Xu et al., 2012; Fig. 2).

The Chengde Basin contains volcanic and volcaniclastic strata ca. 900 m thick, preserved only in the southern and westernmost portions of the basin, and about 2000 m of fluvial and alluvial conglomerates, sandstones, and shales assigned to the Tuchengzi Formation (HBGMR, 1989). These are underlain by andesitic volcanic rocks assigned to the Tiaojishan Formation, which yield U–Pb ages ranging from approximately 160 to 157 Ma (Zhao et al., 2004; Liu et al., 2006). These volcanic rocks are also found farther to the west and east: in the western hills of Beijing, in the Luanping Basin in northern Hebei Province, and in the Niuyingzi and Beipiao basins in western Liaoning Province (Fig. 4). Field observations indicate that there was no significant break in deposition between the Upper Jurassic Tiaojishan Formation and the overlying Tuchengzi Formation. Therefore, the age of the top of the Tiaojishan Formation is the preferred basis for constraining the age of the base of the Tuchengzi Formation. Fig. 4 shows that the youngest zircon U–Pb age for the top of the Tiaojishan Formation is ca. 153 Ma (Cope, 2003; Liu et al., 2006), consistent with the zircon age of 152 ± 3 Ma for the tuff layer near the base of the Tuchengzi Formation (Cope, 2003). The Tuchengzi Formation is overlain, sometimes unconformably, by silicic volcanic rocks of the Lower Cretaceous Zhangjiakou Formation. These volcanic rocks consist mainly of tuffs with intercalated sediments; SHRIMP U–Pb zircon dating in Jiguanshan, Chengde, northern Hebei, has yielded an age of 135 ± 1 Ma (Zhao et al., 2004), slightly younger than the youngest zircon U–Pb age of 139 ± 1 Ma for a tuff layer near the top of the Tuchengzi Formation in the northern limb of the basin (see Fig. 1 of Zhang et al., 2012; Fig. 4). These dates thus constrain the age span of the Tuchengzi Formation to 153–135 Ma.

Fig. 4. Upper Jurassic–Lower Cretaceous stratigraphy of the YFTB, showing the units discussed in the text. Key: 1, coal measures; 2, medium-coarse sandstone; 3, conglomerate and pebbly sandstone; 4, conglomerate and tuffaceous conglomerate; 5, tuffaceous sandstone; 6, crystal tuff; 7, dacite; 8, syenite; 9, andesite and andesite porphyry; 10, andesite breccia and andesitic conglomerate; 11, trachyandesite; 12, andesite-basalt; 13, basalt; 14, U–Pb zircon ages; 15, 40Ar–39Ar hornblende ages; 16, 40Ar–39Ar feldspar age; 17, U–Pb zircon or 40Ar–39Ar data; 19, paraconformity; 20, unconformity; Jf, Upper Jurassic–Lower Cretaceous Tuchengzi Formation; Jt, Upper Jurassic Tiaojishan Formation; Jh, Upper Jurassic Julongshan Formation; Jg, Middle Jurassic Hailangou Formation; Jl, Middle Jurassic Guojadian Formation; Jt, Middle Triassic Erming formation. U–Pb zircon and 40Ar–39Ar data are from: (1) Davis et al. (2001); (2) Li et al. (2001); (3) Swisher et al. (2002); (4) Cope et al. (2007); (5) Peng et al. (2003); (6) Zhao et al. (2004); (7) Gao et al. (2004); (8) Zhang et al. (2005a); (9) Zhang et al. (2005b); (10) Yuan et al. (2005); (11) Davis (2005); (12) Yang & Li (2005); (13) Liu et al. (2006); (14) Hu et al. (2007); and (15) Zhang et al. (2012).
3. Sedimentary facies, provenance, and unroofing as recorded in the Tuchengzi Formation, Chengde Basin

3.1. Paleocurrent data

Paleocurrent indicators were measured across the Chengde Basin from north to south. Paleocurrent directions in the Tuchengzi Formation were determined from the largest flat gravel clasts in gravelly sandstones containing imbricate structures, layers with tabular cross-bedding, and other sedimentary structures. A total of 800 measurements were obtained at 26 sites. The upsection sediment dispersal patterns in the Tuchengzi Formation are shown in Fig. 5. Measurements of the Tuchengzi Formation from the northern part of the basin reveal no upsection shift in sediment dispersal patterns and consistently show dominantly southward paleoflows (Figs. 3 and 5a), suggesting that these sediments were transported from the north. However, upsection paleocurrents measured from the southern limb of the Chengde syncline shift from south-directed paleoflows in the lower Tuchengzi Formation to north-directed paleoflows in the upper Tuchengzi Formation (Figs. 3 and 5b and c). Accordingly, the source region of the Tuchengzi sediments in the southern part of the basin is suggested to have changed from a northern source to a southern one, with the latter being the major source.
3.2. Sedimentary facies analysis

We employed the facies classification proposed by Miall (1978, 1996), in which successions containing at least 50% gravel are denoted G facies, and sandy and sandy-clayey facies are defined as S and F facies, respectively. Some modifications were necessary to include the facies varieties identified in the area, such as the introduction of the Dm facies (massive diamictites). Table 1 lists the lithofacies found in the Chengde area and their respective codes.

The Tuchengzi Formation in the Chengde Basin consists mainly of a set of fluvial and alluvial coarse-grained clastic sediments, and the distribution of every sedimentary facies in the formation is easily observed and measured.

We measured seven stratigraphic sections within the Tuchengzi Formation and four N–S cross-sections through the Chengde Basin, including section A–A₀ in the northern part of the basin, and sections B–B₀ and C–C₀, in the southern limb of the Chengde syncline.

We identified four different facies associations on the basis of lithology, sedimentary structures, and architecture. The four identified lithofacies associations can be matched with proximal fan, mid-fan, distal-fan, and fluvial environments (Figs. 3 and 6), and are described in turn below.

3.2.1. Facies association 1: proximal fan

This facies association is restricted to the southern limb of the Chengde syncline (Fig. 3), where it is characterized by conglomerates that thicken and coarsen to the north. This facies association consists of the Dm (massive diamictite), Gmm (massive, matrix-supported conglomerate), Gcm (massive, clast-supported conglomerate), and, in lower proportions, Gh (crude, cross-bedded, clast-supported conglomerate) and Fm (massive mudstone) facies (Table 1; Fig. 6a).

Intercalations are observed between the Dm and Gmm facies and between the Dm and Gcm facies. The Dm and Gcm facies form meter-scale (2–10 m) packages that predominate compared with the other facies. The Fm facies occurs in the form of layers 1–2 m

<table>
<thead>
<tr>
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<th>Lithofacies</th>
<th>Sedimentary structures</th>
<th>Interpretation</th>
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<tbody>
<tr>
<td>Dm</td>
<td>Diamictite</td>
<td>Massive</td>
<td>Mudflows</td>
</tr>
<tr>
<td>Gmm</td>
<td>Matrix-supported conglomerate</td>
<td>Massive</td>
<td>Debris flows and mudflows</td>
</tr>
<tr>
<td>Gcm</td>
<td>Clast-supported conglomerate</td>
<td>Massive</td>
<td>Turbulent flow as the bottom load in high-energy gravel channels</td>
</tr>
<tr>
<td>Gh</td>
<td>Clast-supported conglomerate</td>
<td>Crude cross-beds and imbrication</td>
<td>Ancient piling up</td>
</tr>
<tr>
<td>Gl</td>
<td>Thin-stratified or lens-shaped, matrix or grain supported gravel</td>
<td>Grading or none</td>
<td>Minor channel fills</td>
</tr>
<tr>
<td>Gt</td>
<td>Clast-supported conglomerate</td>
<td>Trough cross-beds</td>
<td>High-energy stream-channel flow</td>
</tr>
<tr>
<td>St</td>
<td>Sand, medium to coarse, may be pebbly</td>
<td>Trough crossbeds</td>
<td>Dunes</td>
</tr>
<tr>
<td>Sp</td>
<td>Sand, medium to coarse, may be pebbly</td>
<td>Planar crossbeds</td>
<td>Lenticular bars</td>
</tr>
<tr>
<td>Sm</td>
<td>Sand, very fine to coarse, may be pebbly</td>
<td>Parallel bedding, steaming lineation</td>
<td>Planar bed flow</td>
</tr>
<tr>
<td>Sh</td>
<td>Sand, very fine to coarse</td>
<td>Horizontal lamination</td>
<td>Lower flow regime</td>
</tr>
<tr>
<td>Fm</td>
<td>Mud, silt</td>
<td>Massive, desiccation cracks</td>
<td>Overbank or lake</td>
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3.2.2. Facies association 2: mid-fan

3.2.3. Facies association 3: distal fan

3.2.4. Facies association 4: fluvial facies

Table 1
Facies codes, sedimentary structures, and interpretations of the Fenghuoshan and Yaxicuo groups, modified from Miall (1978).

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Fig. 6. Vertical and lateral arrangement of facies associations recorded in the Upper Jurassic–Lower Cretaceous Tuchengzi Formation, Chengde Basin. Proximal fan facies associations a recorded in section B–B₀ and C–C₀; mid-fan facies associations b recorded in section A–A₀; distal-fan facies association c recorded in section A–A₀; fluvial facies association d recorded in section A–A₀ and B–B₀, see Fig. 3.
thick intercalated among the Dm, Gmm, and Gcm facies, as well as millimeter- to centimeter-thick lenses (up to 20 cm) interfingered between Dm layers.

Facies Gmm and Dm are interpreted as having been formed from debris flows and mudflows; the difference between them is the percentage of clay, which is markedly higher in the latter. Transport occurred by viscous flow that deposited clay together with grains of variable size, resulting in poorly sorted deposits. Although they typically represent isotropic deposits, normal or inverse grading and clast alignment can be found where a flow was less viscous (Bull, 1972), as observed for the Dm facies.

The Gcm facies also can be formed by debris flow when fine sediments are absent in the source area, but the possibility that this facies was deposited through turbulent flow as the bottom load in high-energy gravel channels should not be ignored (Miall, 1996).

The Gh facies forms lenticular layers 30–50 cm thick. Gcm facies associated with Gh facies are often the only traces of an ancient accumulation. The lenticular geometry of the strata, the presence of a planar-parallel stratification, and clast imbrication indicate the high energy of the aqueous flow responsible for its formation (Nilsen, 1982). These facies may have been deposited at the bottom of high-energy, straight or braided channels located in the middle or distal alluvial fan. These channels can often be obstructed by debris or mud flow when tectonic pulses reoccur.

The origin of the Fm facies may be related to the formation of water bodies where fine sediment settling occurred. These features are common in the case of the interfingering of depositional lobes and the formation of small depressions subsequently filled by other flows.

These features, combined with the fact these rocks occur only in isolated patches close to the southern margin of the basin, and in contact with volcanic rocks, suggest deposition in the proximal part of a series of coalescing alluvial fans.

3.2.2. Facies association 2: mid-fan

The mid-fan facies association is represented throughout section A–A’, and the facies crops out from west to east in the Tangjiawan to Liugou areas in the northern limb of the Chengde Basin (Fig. 3). The mid-fan facies association is represented by a thick succession of sandstones with intercalations of conglomerate and mudstone, and the association is a mix of Gcm, Sm, Sh, and Fm facies (Table 1; Fig. 6b). The Gcm facies is found only close to the northern margin of the basin, is limited in thickness, and is interpreted as debris flows.

The facies association Sm (massive, fine to very coarse, generally pebbly sandstone) and Sh (laminated fine to medium sandstone), is generally found in the transition to the Fm facies (massive mudstone) in fining-upward sequences. The transition from Sm to Fm occurs in strata with thicknesses of approximately 1–2 m, whereas the transition from Sh to Fm occurs at scales of millimeters to centimeters (not exceeding 30 cm). The association (Sm, Sh, and Fm) can be interpreted as channel overflow deposits formed during flood periods, when the water carrying debris overflowed from the channels and deposited material in lobate sheets. The high-energy, nonchanneled aqueous flow deposited stratified or massive sand; with the loss of energy, the flow ceased, and its suspension load settled out as clayey layers. The lower contact between layers is often erosive, with deformation of the clayey level caused by the sandy flow. These deposits can be found in the intermediate portion of an alluvial fan system, where the slope is shallower and coalescence between fans occurs.

3.2.3. Facies association 3: distal fan

The distal-fan association consists of facies Gt (cross-bedded, clast-supported conglomerate), St (cross-bedded, fine to very coarse, sometimes pebbly sandstone), and Sh (laminated, very fine to medium sandstone) (Table 1; Fig. 6c), and it forms the second segment of the Tuchengzi Formation in section A–A’ (Fig. 3), where...
it is around 800 m thick. These facies occur intercalated in the form of lenticular layers with an erosive lower contact, and range in thickness from 0.5 to 2 m. The presence of trough cross-beds in this association indicates high-energy stream-channel flow. These characteristics might suggest the existence of a distal fluvial system terminal to the alluvial fans.

3.2.4. Facies association 4: fluvial

The fluvial association is characterized by sandstones and conglomerates that fine and thin upwards with normal graded bedding, and mudstones. It contains channel and overbank subfacies that are found in the upper part of section A–A and the bottom part of section B–B (Fig. 3). The fluvial association includes some subfacies of longitudinal sand bars, bedform lag deposits, and floodplain deposits.

The longitudinal sand bars consist of medium to thick beds that are fine- to coarse-grained, characterized by the lithofacies association St and Sp (Table 1, Fig. 6d). The sand bars are usually intercalated with thin mudstones, indicating sedimentary cycles with normal graded bedding, and a single sand-bar sedimentary cycle is typically 0.5–1.0 m thick. This association could represent sand bars that moved downstream or beveled a main-stream channel.

The bedform lag deposits consist of graded conglomerates and sandstones with a lithofacies association of Gl and Sp (Table 1, Fig. 6d). These deposits commonly cover scour surfaces, and they typically grade upwards into longitudinal sand bars. The conglomerates are stratified or lens shaped and grain supported, and the clasts consist of granite, volcanic rock, and sandstone.

The floodplain deposits consist of violet-colored mudstones with intercalated thin or muddy siltstone. These deposits may contain the lithofacies association Sh and Fm. Individual muddy siltstone beds are commonly 0.5–1 m thick, but mudstone beds may be more than 4 m thick. Based on the depositional style, these bedload-dominated fluvial deposits are interpreted to have formed in a braided-river system (Miall, 1996).

3.3. Temporal changes in the gravel components

The composition of gravels and sandstones in a basin is an important indicator of the uplift and erosional history of mountains at the margins of that basin (Hendrix et al., 1996; Hendrix, 2000). The sedimentary rocks of the Tuchengzi Formation in the Chengde Basin are dominated by gravels. At each site investigated, nearly every gravel clast in a specified area of 2 m$^2$ was identified; the number of clasts counted was typically more than 80–100. We compiled three stratigraphic sections (Fig. 5) of the Tuchengzi Formation to show the upward temporal changes in clast composition and abundance.

Fig. 5a shows the conglomerate compositions of the Tuchengzi Formation in the northern limb of the basin. The conglomerate clasts within this section of the Tuchengzi Formation are mainly volcanic rocks with subordinate amounts of granite and gneiss (Figs. 5a and 6a). The granite and gneiss clasts are comparable to the Archean basement rocks and Paleozoic granites that lie north of the Fengning-Longhua Fault (Figs. 1 and 2). Thus, the Tuchengzi Formation in the northern Chengde Basin was most likely derived...
from the ancient basement with a Jurassic volcanic cover north of the Fengning-Longhua Fault. This inference is in agreement with the numerous southward paleocurrent indicators measured throughout the northern Chengde Basin (Fig. 3). Fig. 5b shows the temporal changes in the conglomerate compositions of the Tuchengzi Formation in the southern part of the basin. In the bottom section, the conglomerate clasts consist mainly of volcanic rocks (~50%) with subordinate amounts of granite (~25%) and gneiss (~25%), similar to the clasts in the Tuchengzi Formation in the northern part of the basin. In combination with the southward paleocurrent data (Figs. 3 and 5b), these early Tuchengzi sediments in the southern Chengde Basin are considered to have had the same northern source as the Tuchengzi sediments in the northern part of the basin.

In the dominant, upper section (Fig. 5b), however, the clast lithology changes drastically. The clasts consist mainly of volcanic rocks and banded (or bamboo) limestones (25–95% and 0–35%, respectively). Minor clast components include blue dolomite and chert clasts (5–20% and 5–25%, respectively). The proportion of volcanic clasts decreases markedly upward through the section. Conversely, the proportions of banded limestone and blue dolomite clasts increase upward, and can clearly be linked to the Cambrian–Ordovician carbonate rocks present only in the hanging wall of the Chengde County Fault to the south of the basin. Similarly, the percentage of chert clasts derived from the Jixian Group increases upward in the succession. These temporal trends reflect progressive unroofing and erosion of the Upper Jurassic volcanic rocks of the Tiaojishan Formation followed by the Paleozoic and Mesoproterozoic carbonate rocks to the south of the basin (Figs. 5b and 7b).

Also in the southern limb of the Chengde syncline, we measured another section in the Tuchengzi Formation north of the Sandaohe sheet. As shown in Figs. 5c and 7d, the clasts in this section consist mainly of volcanic rocks (95–100%) with small amounts of chert (0–5%). We interpret that the volcanic clasts were derived from the Upper Jurassic Tiaojishan Formation volcanic cover within the adjacent Sandaohe sheet. The chert clasts were likely derived from the Jixian Group exposed in the Sandaohe sheet as a result of unroofing of the sheet. The dominance of coarse volcanic clasts through this section, in combination with north-directed paleocurrents and the remnants of the Tiaojishan Formation volcanic cover (Figs. 3, 5c, and 7d), indicates a very proximal derivation from the nearby Sandaohe sheet, which experienced rapid uplift and significant erosion of the Tiaojishan volcanic cover. The absence of Cambrian bamboo carbonate clasts together with the rare chert clasts suggests that the rapid uplift of the Sandaohe sheet might have acted as a significant topographic barrier preventing north-vergent delivery of carbonate sediments from the more distal hanging wall of the Chengde County Fault into the southeastern Chengde Basin.

This inferred south-dipping paleoslope is also consistent with the N-S distribution of sedimentary facies association across the basin from mid-fan facies, through distal fan facies, to fluvial facies (Fig. 3). The lack of proximal fan facies at the northern margin was probably because the relief and slope to the north of the basin were not sufficiently steep.

The paleogeography of the southern margin of the basin experienced a significant change after deposition of the lower Tuchengzi sediments in the southern limb of the Chengde syncline. The coarse, poorly sorted conglomerate clasts in the upper Tuchengzi Formation in the southern limb reflect a proximal fan facies (Fig. 3). In combination with the northward paleocurrents recorded from the clasts and clast lithology (Figs. 3 and 5b and c), this proximal fan facies suggests a southern source proximal to the active southern margin of the basin. Uplift and erosion of the hanging wall of the Chengde County Fault to the south of the basin and of the Sandaohe sheet at the southern basin margin were most likely responsible for the coarse sediment influx northward into the southern part of the basin.

4. Discussion

4.1. Basin paleogeography

The prevailing southward paleocurrent data and north-derived basement clasts present in the Tuchengzi Formation in the northern part of the Chengde basin (Figs. 3 and 5a) suggest for these Tuchengzi sediments a primary source region to the north of the basin drained by southward-flowing rivers. North-derived sediments in the lower Tuchengzi Formation in the southern limb of the Chengde syncline (Figs. 3 and 5b) further suggests that those southward-flowing rivers, which dominated in the northern part of the basin, had advanced and delivered sediments to the southern part of the basin. Thus, a southward-inclined paleoslope is implied for the vast majority of the basin, with a depocenter probably located proximal to its southern margin.

The sediments of the Upper Jurassic–Lower Cretaceous Tuchengzi Formation in the Chengde basin, consisting of conglomerates, sandstones, shales, and minor volcanic tuffs, provide a detrital record of the basin dynamics and uplift of the basin margin during the Late Jurassic and Early Cretaceous. Based on the sedimentary evidence presented in this study, we propose the following scenario for the Late Jurassic and Early Cretaceous development of the Chengde Basin.

During the early Late Jurassic, multiple eruptions of extensive intermediate–felsic volcanic rocks occurred in the Chengde area, forming the Tiaojishan Formation (Fig. 8a). These Upper Jurassic Tiaojishan volcanic rocks (ca. 160–153 Ma) unconformably covered the older Jurassic strata (198–180 Ma, Davis et al., 2001; Liu et al., 2012) that were deposited prior to the eruptions, as well as Proterozoic–Paleozoic carbonate rocks and Archean basement.

Following the sedimentation of the Tiaojishan volcanic strata, a series of nearly E–W trending thrust faults bounding the basin were strongly activated as a result of intracontinental N–S tectonic compression. These thrusts include the Fengning-Longhua and Damiao faults to the north, and the Chengde County, Jiyuqing, and Hualiangou-Hedong faults to the south. sediments of the Upper Jurassic–Lower Cretaceous Tuchengzi Formation (153–139 Ma; Figs. 3 and 8b) in the Chengde Basin recorded the uplift and erosion of the basin margins during this time. In the northern Chengde Basin, the sediments in the Tuchengzi Formation were dominantly sourced from the region north of the Fengning-Longhua Fault, Jurassic volcanic rocks, Paleozoic granites, and Precambrian basement gneisses were eroded from the hanging wall of the Fengning-Longhua Fault and transported southward into the Chengde Basin, as demonstrated by the south-directed paleocurrents and comparable conglomerate clasts recorded in the Tuchengzi Formation throughout the northern part of the basin. The Shuangmiao Fault within the basin was not active during this period and made little contribution to the deposition of the Tuchengzi Formation, because the Tuchengzi Formation is cut by this fault and the lithofacies and conglomerate clast lithology of the Tuchengzi Formation are well matched between its hanging wall and footwall (e.g., Cope et al., 2007; He et al., 2007; this study).

During the late Tuchengzi period (ca. 139–135 Ma) prior to the Early Cretaceous Zhangjiakou Formation volcanic eruptions, the Shuangmiao Fault was activated and thrust northward (Fig. 8c), indicating another N–S contraction that was probably much weaker than the shortening during the sedimentation of the Tuchengzi Formation. The folded Tuchengzi Formation in the footwall
of the Shuangmiao Fault (see Section 2.2) may be related to this northward thrusting of the fault.

Coevally, the Tuchengzi sediments in the southern part of the basin (i.e., the southern limb of the Chengde syncline), in contrast to those in the northern basin, were derived from source areas south of the basin. Progressive unroofing of the Upper Jurassic volcanic rocks of the Tiaojishan Formation and the Paleozoic and Mesoproterozoic carbonate rocks from the hanging wall of the Chengde County Fault generated a significant sediment influx northward into the southern part of the basin, and formed a relatively restricted proximal fan facies (Facies Association 1; Fig. 3) overlying the early Tuchengzi sediments of fluvial facies derived from the north. In the southeastern limb of the Chengde syncline, opposite-directed thrusting of the Huailiang-Hedong and Jiyuqing faults during the N–S shortening resulted in rapid uplift of the Sandaohe sheet and formed a steep pop-up tectonic wedge (Fig. 8c), which was originally covered by the Upper Jurassic Tiaojishan volcanic rocks. Significant erosion of the Tiaojishan Formation volcanic cover atop the Sandaohe sheet produced an influx of volcanic materials that were transported northward and rapidly deposited in the southeastern limb of the Chengde syncline, forming a restricted proximal fan facies (Facies Association 1; Fig. 3) of the Tuchengzi Formation in close proximity to the Sandaohe sheet.

This process is reflected well in the Tuchengzi Formation north of the Sandaohe sheet, as indicated by north-vergent palaeocurrent indicators and the dominance (almost 100%) of coarse volcanic clasts within the strata (Figs. 3, 5c, and 7d). The absence of Cambrian bamboo carbonate clasts together with the presence of rare chert clasts indicates that the uplifted Sandaohe sheet acted as a drainage barrier that effectively shut off sediment influx sourced from the more distal hanging wall of the Chengde County Fault. Thus, the source region of the Tuchengzi Formation north of the Sandaohe sheet is different from that of the strata elsewhere in the southern part of the basin. The possibility that the Sandaohe sheet is a klippe resulting from long-distance north-vergent thrusting, as inferred from the interpretation of Davis et al. (1998, 2001), is ruled out in our proposed scenario. If the Sandaohe sheet were a klippe, the associated thrust (the “Chengde Thrust” in previous studies) would have overlain the Cambrian–Ordovician carbonate strata in the hanging wall of the Chengde County Fault (see Fig. 6 in Davis et al., 2001), precluding erosion of those Paleozoic carbonate rocks and their transportation into the southern part of the Chengde Basin, contrary to the sedimentological evidence of the present study. The Sandaohe sheet is therefore an autochthonous pop-up formed during sedimentation of the Lower Cretaceous Tuchengzi Formation.

The north of the basin formed earlier (153–139 Ma), the fault (FL F.) along the northern margin of the basin may control the sedimentary of the Tuchengzi Formation in the early stage. After the sedimentary in the north (>139 Ma), the Sandaohe Sheet at the southern margin of the basin began to uplift quickly and the fault (e.g. CC F.) bounding the basin in the south became strongly active, which resulted in the formation of the matrix strata covering the earlier fluvial facies from the north. This means that the formation of the Chengde County Fault formed later rather than simultaneously with the fault in the north (Zhang et al., 2004a; Cope et al., 2007; Liu et al., 2004).

The evolution of the Chengde Basin ceased before the onset of the Early Cretaceous volcanic eruption recorded at the base of the Zhangjiakou Formation, the zircon SHRIMP U–Pb age of which is 135 ± 1 Ma (Zhao et al., 2004).

After 135 Ma, the North China Craton experienced widespread NW–SE extension, as recorded by brittle normal faults and synkinematic volcanic rocks (Fig. 8d). At the same time, synkinematic plutons were emplaced and synsedimentary half-grabens were filled with continental red beds (Davis et al., 1996, 2002; Meng, 2003; Liu et al., 2005; Charles, 2010).

Our new sedimentological data are in agreement with the interpretation that the northern and southern basin-bounding faults (i.e., the Shuangmiao and Jiyuqing faults) are two separate thrust faults that had opposing north and south vergence (e.g., Zhang et al., 2012) during the development of the Chengde Basin, but are inconsistent with the interpretation that the basin was developed from folding of an allochthon that resulted from long-distance north-vergent thrusting as suggested by Davis et al. (1998, 2001).

5. Conclusions

We analyzed the sedimentary facies, paleocurrents, and provenance of the Tuchengzi Formation in the Chengde Basin for the period of the Late Jurassic and Early Cretaceous thinning in the Yanshan fold-thrust belt. Our main conclusions are as follows.

Four sedimentary facies associations have been identified in the Tuchengzi Formation, corresponding to proximal fan, mid-fan, distal alluvial fan, and fluvial facies. The transport and distribution of the Upper Jurassic–Lower Cretaceous sediments in the Chengde Basin were controlled by the faults bounding the basin.

Paleocurrents and provenance data of conglomerate clasts reveal that the sediments of the Tuchengzi Formation in the northern and southern parts of the Chengde basin were transported from source areas to the north and south of the basin, respectively. The Tuchengzi Formation in the northern part of the basin was derived from erosion of the hanging wall of the Fengning-Longhua Fault. The Tuchengzi Formation in the southern part of the basin was derived partly from the unroofing of the hanging wall of the Chengde County Fault; another important sediment contribution was derived from the rapid uplift and erosion of the Sandaohe sheet, which is located in the southeastern limb of the Chengde syncline.

The Sandaohe sheet is not a klippe resulting from long-distance north-vergent thrusting, but an autochthonous pop-up wedge generated by N–S shortening during the sedimentation of the Lower Cretaceous Tuchengzi Formation.

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